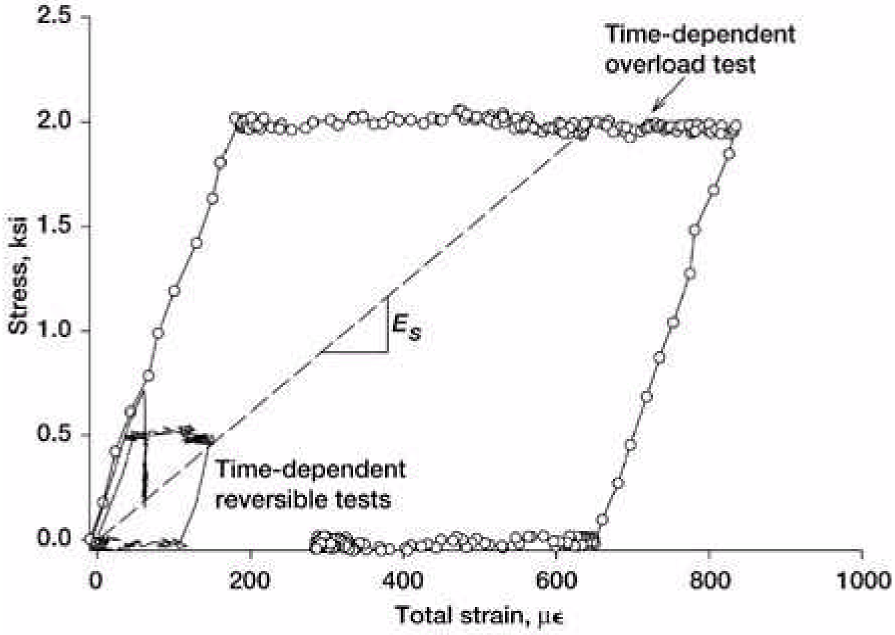
Time-Dependent Reversible-Irreversible Deformation Threshold Determined Explicitly by Experimental Technique

Structural materials for the design of advanced aeropropulsion components are usually subject to loading under elevated temperatures, where a material's viscosity (resistance to flow) is greatly reduced in comparison to its viscosity under low-temperature conditions. As a result, the propensity for the material to exhibit time-dependent deformation is significantly enhanced, even when loading is limited to a quasi-linear stress-strain regime as an effort to avoid permanent (irreversible) nonlinear deformation. An understanding and assessment of such time-dependent effects in the context of combined reversible and irreversible deformation is critical to the development of constitutive models that can accurately predict the general hereditary behavior of material deformation. To this end, researchers at the NASA Glenn Research Center at Lewis Field developed a unique experimental technique that identifies the existence of and explicitly determines a threshold stress κ, below which the time-dependent material deformation is wholly reversible, and above which irreversible deformation is incurred.

This technique is unique in the sense that it allows, for the first time, an objective, explicit, experimental measurement of κ. The underlying concept for the experiment is based on the assumption that the material's time-dependent reversible response is invariable, even in the presence of irreversible deformation. The first step is to conduct a test (preferably two) where the time-dependent deformation response is wholly reversible. Shown in the figure are two such tests on the titanium alloy TIMETAL 21S at 650 °C; one is a creep test (constant stress hold) at 0.5 ksi, and the other is a stress relaxation test (constant strain hold) at 60 $\mu\varepsilon$.

Both tests exhibit shutdown of the time-dependent response, which is generally best seen in a time-based plot. For example, after approximately 5 hours of creep at 0.5 ksi, the creep strain rate went to zero (i.e., all creep shut down), and it remained in that state for 7 more hours. Upon unloading to zero stress subsequent to 12 hours of stress hold, the data revealed that the creep strain was fully recovered in time. The viscoelastic creep shut down at a strain of approximately 140 $\mu\varepsilon$. The stress relaxation test behaved in a similar way, terminating at approximately 0.23 ksi with subsequent full strain recovery observed. The stress-strain slope E_s determined by the termination point(s) represents the time-independent stiffness at 650 °C and is indicative of an infinite limit stress for the spring within the standard solid viscoelastic model (see ref. 1).



Time-dependent deformation tests provide explicit determination of the reversible-irreversible threshold stress ($\kappa = \sigma_{applied} - \varepsilon_{IR} E_s$*) by using viscoelastic subtraction for a titanium alloy at 650 °C.*

The value of κ is determined by loading a sample beyond κ (well into the irreversible range) and holding the load long enough to allow the viscoelastic (time-dependent reversible) response to be fully exhausted. This is termed the "overload" test in the figure. The minimum hold time for this test should correspond to the shutdown time required for the viscoelastic tests. Subsequent to this hold period, where the accumulated creep strain results from both time-dependent reversible and irreversible behavior, the specimen is unloaded and given sufficient time to allow for full recovery of the time-dependent reversible strains. From this data, the excess equilibrium stress corresponding to the irreversible portion of the induced strain is calculated ($\sigma_{\chi e} = \varepsilon^{IR} E_s$) and then simply subtracted from the stress level at which the test is performed to obtain κ ($\kappa = \sigma_{\text{applied}} - \sigma_{\chi e}$). This value effectively represents the upper bound of the viscoelastic regime and, thereby, represents the threshold of irreversible behavior. Appropriately, this technique has been termed "viscoelastic subtraction." Values of κ obtained from the viscoelastic subtraction technique were initially verified with more tedious, so-called probing experiments designed to establish the threshold of yield and extremely slow-rate proportional limit tests (ref. 2).

References

1. Saleeb, A.F.; and Arnold, S.M.: A General Reversible Hereditary Constitutive Model: Part I—Theoretical Developments. NASA TM–107493, 1997.

2. Arnold, S.M.; Saleeb, A.F.; and Castelli, M.G.: A General Reversible Hereditary

Constitutive Model: Part II—Application to a Titanium Alloy. NASA TM–107494, 1997.

Glenn contact: Dr. Steven M. Arnold, (216) 433–3334, Steven.M.Arnold@grc.nasa.gov

Author: Michael G. Castelli and Dr. Steven M. Arnold

Headquarters program office: OAST

Programs/Projects: HITEMP